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Fractal properties of settlement system as factor of its sustainability: Ural in the 18th–20th centuries

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Abstract. The thoughts by N. Salingaros on sustainable design, translated and introduced into scientific discourse by the author of the paper, served as a basis for primary analysis of the layout of a small industrial town and the settlement system of the industrial part of the Urals. Invariable features of the town layout have been reconstructed based on the materials by W. de Gennin and modern historical and cultural studies. The paper shows the elements of fractality and self-similarity in the layout of small industrial towns and in the Ural settlement system, which correspond to the parameters established by N. Salingaros. A conclusion is made about sustainability as an additional internal resource of the settlement system in the region.

1. Introduction

Nowadays small industrial towns of the Ural region, which appeared mainly in the 18th–20th centuries, experience difficult times. Designed as single-industry towns, during the post-industrial period they faced the issues of diversifying economy and environment, as well as negative demographic indicators, population migration to big cities (especially metropolitan agglomerations), underestimation of their potential by municipal administrations and population. The state support for different types of Russian settlements in crisis and post-crisis environment is based on spatial specialization. In most cases it is sporadic, and is associated with two prevailing types of transformation of small and medium-sized Russian towns: supporting the town-forming enterprise, and supporting economic and social development within the area [1]. The image is complemented by the deterioration of historical and architectural heritage, and, to a large extent, by the slow thinking of experts employed in architecture [2-4]. Despite criticism of the overall evaluation, those cities, as well as the whole settlement system of the region, possess an unappreciated internal resource (not an external one, e.g. such as trade retailers [5]), which increases the system's resistance. This resource implies the arrangement of the system itself [6].

The contemporary strategy of preservation, mainstreaming, and use of historical, architectural and urban planning capacity of the region is to be related to economy and social policy [1,7,8]. It "turns over" the conventional hierarchy, assigning the heritage to the role of a foundation for many economic processes in small industrial towns, and working more systematically with it [8,9]. However, the heritage itself has not yet been studied thoroughly, not just at the level of the description of its appearance but at the level of its internal arrangement.

Based on the methodology of the research on the sustainability of architectural and urban planning systems, made by Ch. Alexander [10] and N. Salingaros, we shall summarize the empirical material and data for small industrial towns of the Urals. The works by N. Salingaros have been and continue being translated by the author of this paper, and are now available to Russian-speaking readers [11,12]. For the first time the fractal theory as a basis for the sustainability of complex systems is being projected to the settlement system of the Ural region. Each idea by N. Salingaros is preliminarily matched with some specific historical, architectural and urban planning material, and the fractality of the Urals settlement system is confirmed. Here, we treat the concept of "sustainability" not in economic terms but rather in terms of architecture and urban planning [13]. By sustainable system we mean the system with architectural and urban planning features that are similar to the properties of natural sites and, thus, consider both the needs of people and of their natural and artificial environment to the greatest extent possible.

The purpose of the paper is to prove the following hypothesis: the settlement system of the Ural factory towns possesses additional sustainability, which has not been fully appreciated by experts in management and urban development. The comprehensive study of this sustainability provides resources for socio-economic and socio-cultural development of the area, and also strengthens its identity and distinctiveness [6,14]. Since not all data on architectural and urban planning sites are now available, a particular result of the work can be represented in the form of the near future actions aimed at systematic measurements, photographic evidence, distance measurement, etc. At the same time this result corresponds to the current trend of shifting the focus from the activity on conserving the heritage to its mainstreaming and development [3,7,15], which is a possibility to maintain the traditions of the Ural architects.

2. Literature Review

Since the topic is interdisciplinary, a review of the sources allows to show its main components.

The problematic factors in the existence of small industrial towns (single-industry towns, factory towns) of the Ural region have been studied by such experts as E. G. Animitsa; Yu. G. Lavrikova, S. G. Pyankova; V. A. Larionova; V. Ya Lyubovny; A. N. Maslov; V. Mazur; I. D. Turgel, and others. They mention negative demographic and economic trends, the need to diversify the economy, environmental issues, etc., but do not analyse towns as a single, most notably spatial, system [1,14].

The history of establishment and development of this system has been mainly studied by experts in culture and history – such as S. V. Golikova [16], R. Fedorov [7], V. I. Baydin et al. [17], V. Belov [18], M. B. Larionova [19], T. E. Kameneva [20], and others. They logically put an emphasis on social structure and everyday life of these towns, and on the study of particular objects and phenomena, whereas much less attention is paid to the peculiarities of urban planning layout, although in his memoirs written in 1735 W. de Gennin, the founder of the system of factory towns in the Urals [21], gives a lot of reasonable and evidence-based urban planning directions, which are discussed below. N. S. Alferov [22], E. N. Bubnov [23], A. V. Dolgov, R. M. Lotareva, A. Yu. Kaptikov study the architecture of particular buildings and complexes.

The development of architectural issues on the basis of systematic approach [24] and fractal theory is studied by the following researchers: M. P. Zakharova and V. A. Kolyasnikov [25], V. V. Isayeva and N. V. Kasyanov [26], but this topic is little developed in the Russian theory of architecture.

Finally, a separate cluster of works is dedicated to conservation, rehabilitation, and mainstreaming of the historical and architectural heritage. They contain interesting examples and suggestions, which can be scaled out in a fractal settlement system, thus increasing their effectiveness. Among the authors of these works we can mention such names as P. M. Shulgin [27], E. Bowitz and K. Ibenholt [28], I. Schmelzer [9], T. Bystrova [29], B. M. Valchak, G. V. Babenko, E. Belyakova, K. A. Gryaznukhin, G. F. Gudkov [30].

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3. Methodology

Brief Description of Sustainable Architecture, as set out by N. Salingaros, who, in turn, develops the thoughts of Ch. Alexander [10]. They treat the whole town and its particular architectural elements as "an organized system, which needs to harmoniously fit into the natural ecosystem to survive" (G. Papanicolaou) [11]. And although he mainly focuses on the development of algorithms for sustainable design and the criticism of modernistic and deconstructivist architecture, in the first chapters of his work the said author also mentions a number of properties of fractals, which enhance the sustainability of any complex system.

N. Salingaros talks about the universal scaling hierarchy, which also has several forms. Both ascending and descending correlations of components and subsystems within a complex sustainable system can be close to the Fibonacci sequence (1, 3, 8, 21, 55, 144 ...) to the maximum extent possible – and thus approximate and random "intermediate" proportions will weaken the system. Another option, similar in its effectiveness, is provided by a geometric sequence of logarithmic constant ($e = 2,72$) exponents (it determines the shape of animals' horns and antlers, shells, etc.). "The rule of three" is very simple (with reference to ancient architecture and medieval architecture of the Western Europe, and to the research by Ch. Alexander "The Nature of Order"): "make sure that there is something that is three times bigger than the facility you are constructing, and something that makes up one third of the facility you are constructing" [11].

N. Salingaros believes that the universal scaling hierarchy emerges in any pre-modernistic architecture, no matter if it is vernacular, or executed in various styles. The experts formulate the principles of their work in other terms or formulas, but eventually – be it deliberately or spontaneously – come to the solutions that meet the requirements of adaptability. Let us demonstrate some of them.

Mentioning the golden section in particular, N. Salingaros emphasizes that he examines not a rectangle aspect ratio but rather the sequences of lengths of various scale that can be found within a certain architectural site. Design or sustainability evaluation of this site are not limited to the façade or some subspace, but take place volumetrically [11]. N. Salingaros uses the notion of "3-D fractals" and similar terms in order to emphasize the one-dimensionality of modernistic architectural solutions that multiply the plan of one floor. Accordingly, regardless of the approach to scaling – be it contraction or expansion – a sustainable object is modelled in three dimensions, whereas its particular elements are partially self-similar, which allows the system to store information about itself in a compressed form (Cosmati mosaics, layouts of villages of African nations, etc.).

N. Salingaros emphasizes that the rules of sustainable architecture of different scales can and should imply the calculation of proportions of a consecutive series of elements (stair tread – flight of stairs – height of the floor – building arrangement) rather than the indication of the exact sizes. The variability (rather than monotonous repetition) is essential within any sequence. Universal scaling is combined with combinatorial complexity.

Such proportional consistency of elements not only contributes to the sustainability of the architectural object itself but also makes it adapted to the human perception. The human sensory system has developed adjusting itself to communication with other forms of life, therefore, natural geometry optimizes the state of body and emotions. Accordingly, military fortifications, for instance, are not human-friendly – because they are meant to frighten people, and may not fit into a system of universal scaling.

N. Salingaros briefly but aesthetically and functionally interesting dwells on the topic of borders and edges, arguing that in a sustainable system "any connection of elements requires that edges should be defined" [11]. Unfortunately, the structural parameters of landscapes or spatial contexts as they are, in which an architectural site exists, are left beyond the author's consideration: acknowledging their presence and diversity, he does not look for any structural arrangement outside the building. The experience of studying the Ural settlement system shows that it can and should be done. Formatting the title, authors and affiliations

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4. Comparison of the parameters of the system of Ural small industrial towns with the features of sustainable architectural sites, according to Ch. Alexander and N. Salingaros

"Let us take some hypothetical (approximated) dimensions obtained from the universal scaling hierarchy: 1 mm, 3 mm, 8 mm, 2 cm, 6 cm, 14 cm, 38 cm, 1 m, 2.6 m, and so on. They correspond to the human size" [11].

4.1. Three levels of architectural layout of factory towns

The structure of the mining settlement system can be represented in the form of at least three levels of architectural layout, and we have to find out the degree of their self-similarity. The levels are the following: 1) the centre of an industrial town with a dam, a pond, and a factory; 2) the town itself; 3) the whole settlement system comprising about 200 industrial settlements. And, although E. V. Ponomarenko refers to the layout of a particular town (Zlatoust) as "primitive" [5], we do not agree with this, and insist on a high degree of consistency and rationality of residential structures. Another thing is that the town, which was created to meet the industrial needs, did not imply any special conveniences for most of its residents, especially if these conveniences are evaluated from the contemporary point of view.

Each of the indicated levels can afterwards be calculated according to the parameters suggested by N. Salingaros. W. de Gennin indicates the following construction rules that have turned into invariable features of Ural industrial towns [21].

- Internal system communications within a large-scale complex system are defined not only by roads (from the factory to the deposit, from the factory to another factory of the given owner), but also by rivers. The factory is established near a small river but the delivery of products is carried out via large rivers (the Chusovaya, the Kama) [13,18,30].
- When choosing a place for living account is taken of the fact that for convenience and speed of damming it for one or two seasons, the river should not be too wide (30–70 m) though water-abundant, with the banks approximately equal in height. The town layout's orientation in the cardinal directions, which used to have a sacred meaning in more ancient towns, is not kept here. Production based on power and natural resources serves as an organizing principle of the town [17].
- Initially, the factory (the town-to-be) was built within not more than 15 km away from the deposit of iron or copper ore, in order to reduce the amount of transportations and not to tire the horses [16,17]. The average distance between the towns is from 15 to 45 km.
- The terrain should be taken into account while choosing the location for the dam so that the pond might be created, and the forest and natural resources would be close by [15,16]. The pond should be deep enough so that not to freeze through in winter, and the production should not stop. It is the dam's location that is actually a point, which forms self-similar elements of the settlement system within a mountain range having certain rhythm and structure (including that of its layers and rocks).
- The dam is placed across the river and gives rise to one of two major highways of a settlement (Figure 1).
- The dam is built very carefully [2], becoming an integral part of the landscape. The existing lakes are supplemented by artificial ponds that change the image of the area.
- The pond should be moderately large, so as not to freeze through to the bottom during severe winters (its average depth being 3-4 m). The pond also becomes the town's main water surface, which is important both economically and aesthetically.

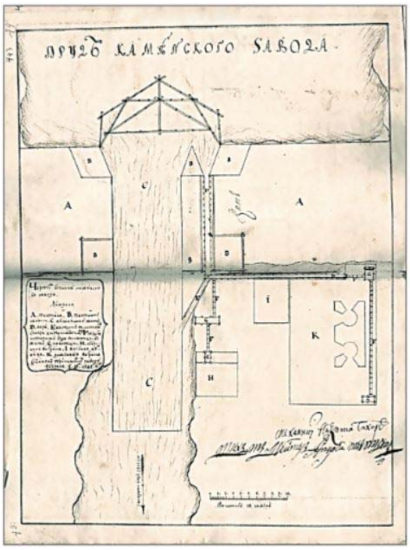

Figure 1. Layout of Kamensky plant. 1741. Drawn by W. de Gennin. Taken from the book "Industrial Heritage of the Urals in Photos" by N. S. Korepanov and E. A. Rukosuev, Ekaterinburg, 1993.

- The factory is located at the intersection of the river and the dam, below the dam level. The elevation difference between a factory management building and a church can exceed 10 m; the factory management building is located near the factory workshops, and the town itself goes "upwards". The semantically and structurally significant central part, going upwards in "conventional" towns, "goes" downwards here, just as the town itself, which is located not at the peak, as it might be the case with a fortress, but between the mountains. The centre links the town (civilizational origin) and the mountain (natural origin) [29].
- The town can be located both on one, and on both sides of the dam, but it has a centre of compact size anyway, where all functions of the town – production, management, spiritual life, education, and trade – are located within the area of about 500x500 meters.
- The settlement density is even, without becoming denser towards the town centre.
- The town with rectangular street grid naturally includes a large number of simple, rectangular architectural sites of average height, which are human-scaled [2,23,25]. The cathedral and the factory chimneys are visual dominants of the town.
- The town is located in the mountains, which are natural equivalents of "borders' thickening" mentioned by N. Salingaros [11].
- The town is built into the system of towns and settlements, which have similar structure. Where the mountains and hence, their resources, end, the towns are engaged in trade or other kinds of production – thus the settlement system sets its own limits itself. The nature of towns (Talitsa, Kamyshlov, Irbit) is changing at the "entrance" and "exit" from the region – they become commercial and "suburban-like".

This data are yet to be mathematically verified but it would be safe to assume that they look quite convincing for future research.

The emerging network has both flexibility and sustainability due to its tight integration with the natural foundation. Its elements are self-similar at different levels, from wooden architecture [10] to urban planning layout, which enhances their sustainability and internal coherence of the system. The system itself is quite dynamic, the mountains do not impede road construction and intensive traffic: being built on small rivers, the towns deliver their products to the central part of Russia via the larger rivers, and later by rail.

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4.2. Connection between the settlement system and the terrain relief

Let us extend the concept by N. Salingaros up to the connection of the settlement system with a well-structured mountain terrain having fractal properties. Being aware of the rules of choosing the location for a pond and a factory, we analysed the layouts of 10 (out of more than 100) small industrial towns. The terrains were modelled via the following web service: http://22dx.ru/qth/elevation.html. The reasoning of this research runs as follows: the dam is placed perpendicular to the river, the town's main street running along the dam and going on further, whereas the rest of the streets are strictly perpendicular, since the urban core creators adhere to a regular layout, especially in the 18th century. The factory is located on one side of the dam, the factory management office and a house of factory owners are a little bit away from it, a church and later in the second half of the 19th century – a shopping street being close by.

The towns were selected randomly in this part of the research, and the work can be continued in the future. For now it can be assumed that the solution was "suggested" by the terrain relief rather than by some typical plan.

A stunning example of complete resemblance of the layout with different proportions (by the way, just according to the 3: 1 rule) is given by the towns of Nevyansk and Sysert (Figure 2, 3.).

Figure 2. Terrain relief along the line of continuation of the dam. Nevyansk (founded in 1701).

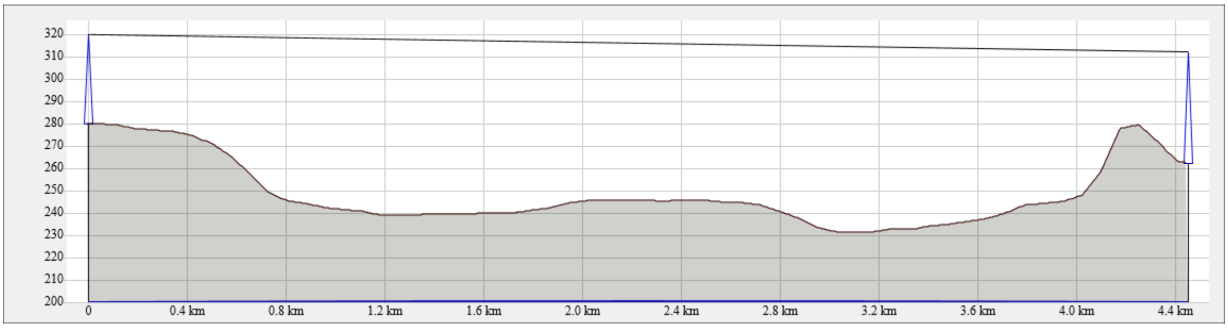

Figure 3. Terrain relief along the line of continuation of the dam. Sysert (founded in 1732).

In addition, small industrial towns of the Urals founded in the 18th and 19th centuries, have a dense and compact historical core. The core is filled with objects, including factory workshops and buildings [22], executed on a good-quality architectural level, often in the classical style referred to by N. Salingaros as having fractal properties. A. E. Gutnov also mentions the structure-forming role of the centre [31], what is important for contemporary urban processes too [32-34].

5. Conclusion

Given the comparison of the features of sustainable adaptive architectural systems described by N. Salingaros with the empirical data on the settlement system of small industrial towns in the Urals, the

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statement about a high degree of architectural and urban planning sustainability of this system can be considered proven. Further proof needs additional data. The results of this proof, in turn, will allow to create modern forms that do not contradict the sustainability of architectural and urban planning regional solutions. In this regard N. Salingaros notes: "When designing various buildings and under different initial conditions, we can use the adaptive design algorithm together with the language of conventional forms. ... Though the same algorithm was used, buildings and towns acquire their uniqueness while adapting to the local conditions. In addition, there are many different adaptive design algorithms found throughout thousands of years of the human history" [11].

The ideas of sustainable algorithmic architectural design, suggested by N. A. Salingaros, are, among other things, a good tool for analysis and expert evaluation of existing architectural sites and systems.

Rethinking the attitude to the heritage has long-term economic effects for certain towns and for the region as a whole [33]. The sustainability of the settlement system of the region can be referred to a number of internal resources of socio-economic and cultural development.

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